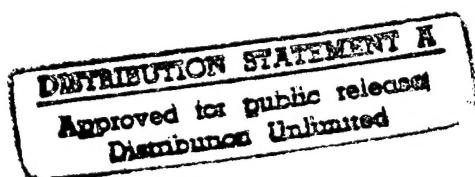


Technical Report 13703
November 1996

Electromechanical Actuators for Active Suspension Systems

by Alexander R. Kovnat
Mobility Exploratory Projects Team

U.S. Army Tank-Automotive Research, Development
and Engineering Center
Warren, Michigan 48397-5000



19970602 103

The contents of this report were prepared for an Advanced Technology Assessment Report (ATAR) funded by Headquarters, Army Materiel Command.

DATA QUALITY IMPROVED 1

TABLE OF CONTENTS

1. Introduction	1
2. Executive Summary	3
3. Background and Technology Description	5
4. Requirements for Electromechanical Suspension Actuators	11
5. Case Studies in Electromechanical Suspension Actuators .	13
5.1 University of Texas Center for Electromechanics .	13
5.2 Linear Electromechanical Actuator Studies for the CUCV	
.	19
5.3 Electromechanical Suspension Actuators based on Screw	
Translation Mechanisms	25
6. Developments in Motor and Actuator Concepts Applicable to	
Electromechanical Active Suspensions	29
7. Problems, Prospects and Issues with Electromechanical	
Suspensions	33
8. Military, Commercial and National Importance of	
Electromechanical Actuators	34
9. References	37
Distribution List	40

List of Figures

Figure 1. Semiaactive versus active suspension.	7
Figure 2. Electromechanical Active Suspension (EMASS) test setup.	14
Figure 3. EMASS actuator.	15
Figure 4. Simulated response of EMASS over 8 inch bump . . .	17
Figure 5. UT-CEM linear actuator design concept.	19
Figure 6. Tubular linear induction motor topology.	21
Figure 7. FMC tubular linear induction actuator design. . .	22
Figure 8. Reluctance motor/actuator principle.	24
Figure 9. Ford Motor Company ball-screw active suspension actuator patent.	27
Figure 10. Axial-flux, reluctance-type rotary actuator. . . .	30
Figure 11. Two-stage, axial flux permanent magnet machine	
	31

1. Introduction

Electromechanical suspension actuators are devices intended to provide the force input called for by motor vehicle active suspension systems.

Experimental active suspensions have been devised, in which hydraulic actuators provide the force input. Such systems leave much to be desired regarding safety to equipment and personnel. In addition, hydraulic actuators require an electromechanical valve to interface the electrical and hydraulic aspects of the overall system. Accordingly, electromechanical actuators are being studied as an alternative approach to active suspension design. Such actuators would provide a direct interface between electrical/electronic controls and the suspension dynamics, eliminating the need for hydraulic systems and their attendant problems of leakage and vulnerability to battle damage.

The report that follows, describes the reason for studying electromechanical actuators, requirements such devices must meet, and various development programs. In addition, this report also describes various electric motor and actuator concepts that could serve as a point of departure for future electromechanical actuator development.

2. Executive Summary

The report presented here, was first issued as the second part of a two-part Advanced Technology Assessment Report (ATAR). The purpose of that ATAR was to provide a description of world-wide developments in both field dependent fluids and electromechanical actuators.

Electromechanical actuators, like field dependent fluids, offer a means of interfacing an electrical/electronic control system directly to the mechanical dynamics being controlled. While field dependent fluids offer rapid and reversible variation in resistance to force and motion when subjected to an applied electric or magnetic field, an electromechanical actuator provides force input into a suspension or other system.

The chapters which follow provide a background and technology description, requirements, and examples of development programs involving electromechanical actuators. In addition the report describes motor and actuator technologies which may be useful in future actuator development programs, problems and issues to be resolved, and the commercial and military importance of these devices. A list of references constitutes the final chapter.

3. Background and Technology Description

Electromechanical actuators, like field dependent fluids, are a method of attaining a direct interface between the electrical and mechanical portions of an overall system. Electro- and magnetorheological fluids would be used in conjunction with semiactive suspension or vibration absorption systems. In such systems, there is no force input. One merely adjusts the damping characteristics to suit changing circumstances. With active suspensions or vibration control systems, an actuator provides force input to counteract undesired motion (See Figures 1a and 1b).

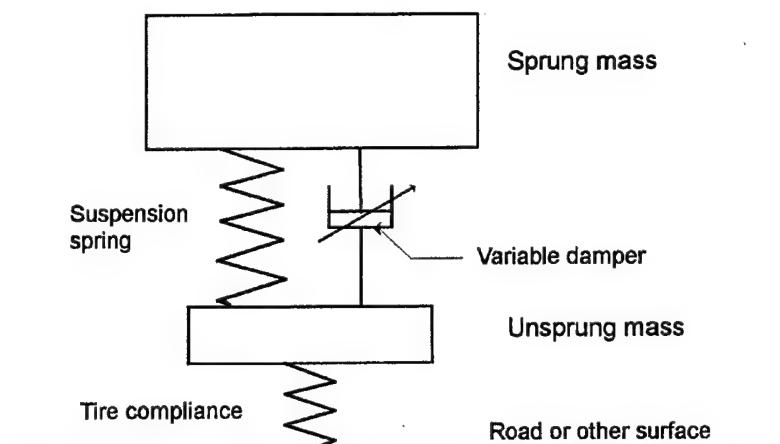
Experimental active suspension systems have been devised. These systems use hydraulic actuators acting in parallel with vehicle springs or torsion bars. Hydraulic fluid is admitted to the actuators by valves which in turn are actuated by signals from a control system. The necessity of a hydraulic system means one must provide a pump, servo valves, and suitable conduits for fluid under pressure.

In the active suspension system devised for the High Mobility Multipurpose Wheeled Vehicle (HMMWV), hydraulic fluid is supplied at above 2000 psi pressure. Such systems are prone to leakage and sudden bursts. Bursts of high pressure hydraulic fluid lines are dangerous to people and destructive to equipment. Hydraulic systems are also vulnerable in combat. Experience demonstrates that many fires involving tracked combat vehicles are either started or aggravated by hydraulic fluids.

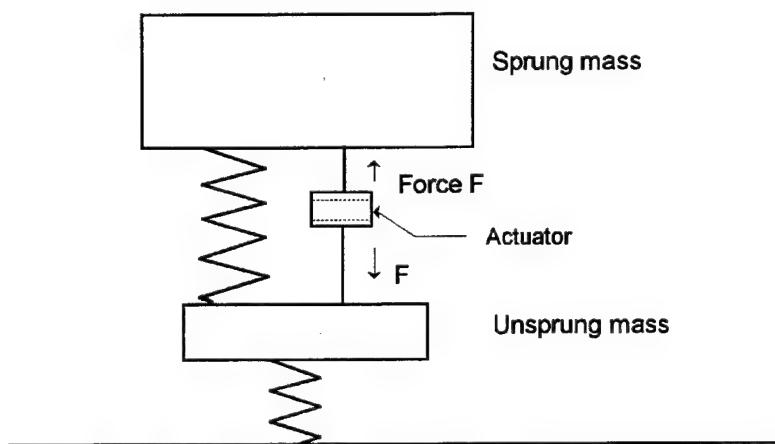
In addition, since the control system is by nature electronic, an interface is needed between the electrical and hydraulic parts of the overall system. This interface takes the form of servo valves, whose inertia adds a time delay to the overall system dynamics.

When electromechanical actuators provide the force input required by an active suspension, the actuator interfaces the control system directly to the suspension dynamics, without the need for hydraulics as an intermediary. There is no problem

with leakage, and no need for valves.



(a)



(b)

Figure 1. a. semiactive suspension. b. active suspension

Electric actuators and motors are similar in many respects, in that they both convert electric energy to mechanical energy. While a motor's purpose is continuous rotary motion, actuators have traditionally been positioning devices.

Like motors, electric actuators come in a variety of forms. They may be rotary or linear. They can be designed for direct or alternating current. A.C. actuators may be induction, reluctance, or synchronous. Direct current actuators may use a mechanical commutator, or the necessary commutation may be performed by electronic switching. Rotary motors and actuators may be radial or axial, i.e., the stator and rotor elements may be arranged concentric with one another, or side-by-side. Reluctance-type motor/actuators can operate on alternating current, or direct current subjected to appropriately timed switching.

Permanent magnet (PM) motors and actuators have made great strides in recent years. Neodymium-iron-boron (Nd-Fe-B) permanent magnets offer greater strength than previously available materials. Accordingly, PM-based actuators for suspension systems may be feasible.

4. Requirements for Electromechanical Suspension Actuators

A variety of motor types have been evaluated in the quest for a commercially viable electric vehicle. For an electric vehicle motor, one desires constant rated power output over a wide RPM range, high torque, high efficiency, high power to weight ratio, and ability to function as a generator when the vehicle is slowing down, so as to return some energy to the batteries.

Electric suspension actuators must demonstrate rapidity of operation, high force capability in proportion to size and weight, sufficient length of stroke, and reasonable cost. It is also desirable for a suspension actuator to function in all four quadrants, i.e., convert electric power to force or vice versa when operating in either direction. Unlike a propulsion motor, a suspension actuator has to be capable of rapid reversal.

The active suspension application is fundamentally different from other actuator applications in that what is desired is not accurate positioning, but constancy of force over the length of actuator stroke or (for a rotary actuator) angular displacement. Whereas an actuator in a machine tool is a positioning device, in a suspension it is a force device.

5. Case Studies in Electromechanical Suspension Actuators

5.1 University of Texas Center for Electromechanics

Professor Joseph Beno and his team at the University of Texas Center for Electromechanics have done extensive work in electromechanical suspension actuators. One of Dr. Beno's designs is the Electromagnetic Active Suspension System (EMASS), developed for the Abrams main battle tank¹.

For this application, a linear actuator would have to have a stroke of 20 inches, which is excessive. In addition the force needed to continuously support an M1A1 road wheel, would result in an actuator that would be impractically large and heavy. Such an actuator would also consume unacceptable amounts of electric power. Accordingly, a rotary actuator was developed for this application. In the rotary active suspension configuration developed by Professor Beno, an air spring supports the static weight resting on a given road arm. The actuator then needs only to provide dynamic forces in accordance with the EMASS control algorithm. Simulations demonstrated that an actuator capable of 2500 Newton-meters of torque would result in significantly improved ride quality².

The EMASS was evaluated on a test setup similar to the "quarter car" method used to evaluate wheeled vehicle suspension components (Figure 2). The sprung mass was a 5 ton concrete block, which is approximately the weight borne by one Abrams roadwheel.

EMASS was designed in accordance with the constant force concept, whereby the actuator adds to or subtracts from the force offered by springs or torsion bars so as to maintain a constant upward force on the sprung mass. Since the net force (which includes gravity) on the sprung mass is zero, a perfectly smooth ride results because there is no acceleration

TEST BED GENERAL ARRANGEMENT

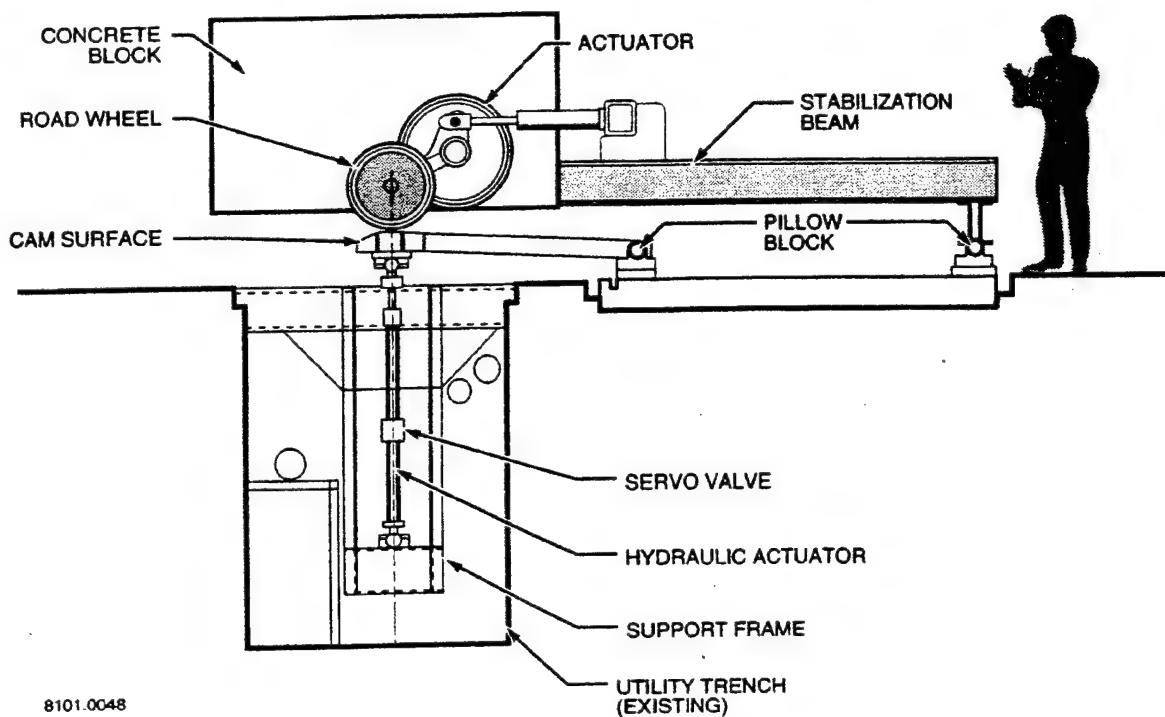
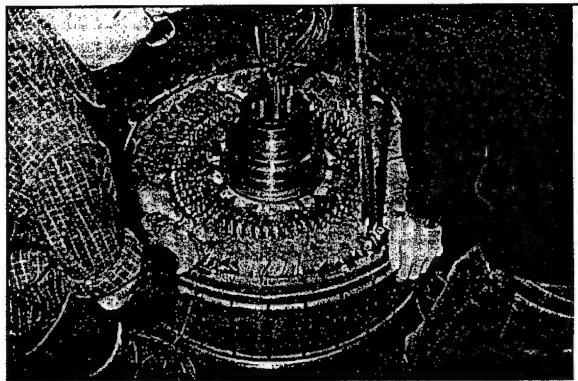


Figure 2. EMASS test setup

(Ingram, S.K. and J.H. Beno, Design, Fabrication, and Test of a High Torque Rotary Actuator for a Main Battle Tank Active Suspension Proof of Principle Demonstration, U. of Texas Center for Electromechanics, Austin, TX

of the sprung mass as the vehicle travels over uneven terrain. In practice, with a rotary actuator it is easier to maintain constant torque. The actual force varies slightly as a function of road arm angle, and also varies somewhat because of the need to negotiate hills (as opposed to bumps). Hence the system is designated a near constant force suspension (NCFS).

The actuator (see Figure 3) is a 32 pole, electronically commutated DC motor with separately excited field and armature. Modeling of the UT-CEM suspension concept indicated 2500 Newton-Meters of torque would be sufficient, but the actuator



S 8101.0111

Figure 3. EMASS actuator
(Presented at kickoff meeting held
July 11, 1996 at TARDEC, Warren,
Michigan)

can provide up to 5000 N-m if necessary. Maximum RPM is low (the equivalent of 85 RPM), but the actuator must be capable of rapid torque fluctuations and must be rapidly reversible. Diameter must be no greater than 30 inches, and mass minimized as much as possible. The actuator drives the road arm directly.

Although there is a weight penalty, an iron-core rather than an air-core machine was devised because of the low efficiency and resulting high heat generation characteristic of the latter. Both $\mathbf{J} \times \mathbf{B}$ (i.e., current interacting with magnetic field) and reluctance-type actuators were studied, but the former was chosen because of time and resource limitations. Homopolar machines offer the advantage of being true torque-producing devices, but were rejected because of high current requirements. DC-type machines were recognized as compatible with future all-electric tracked combat vehicles, and hence this is what was chosen. The UT-CEM actuator is of the radial gap type, thought axial gap machines are also a possibility for future rotary actuator designs.

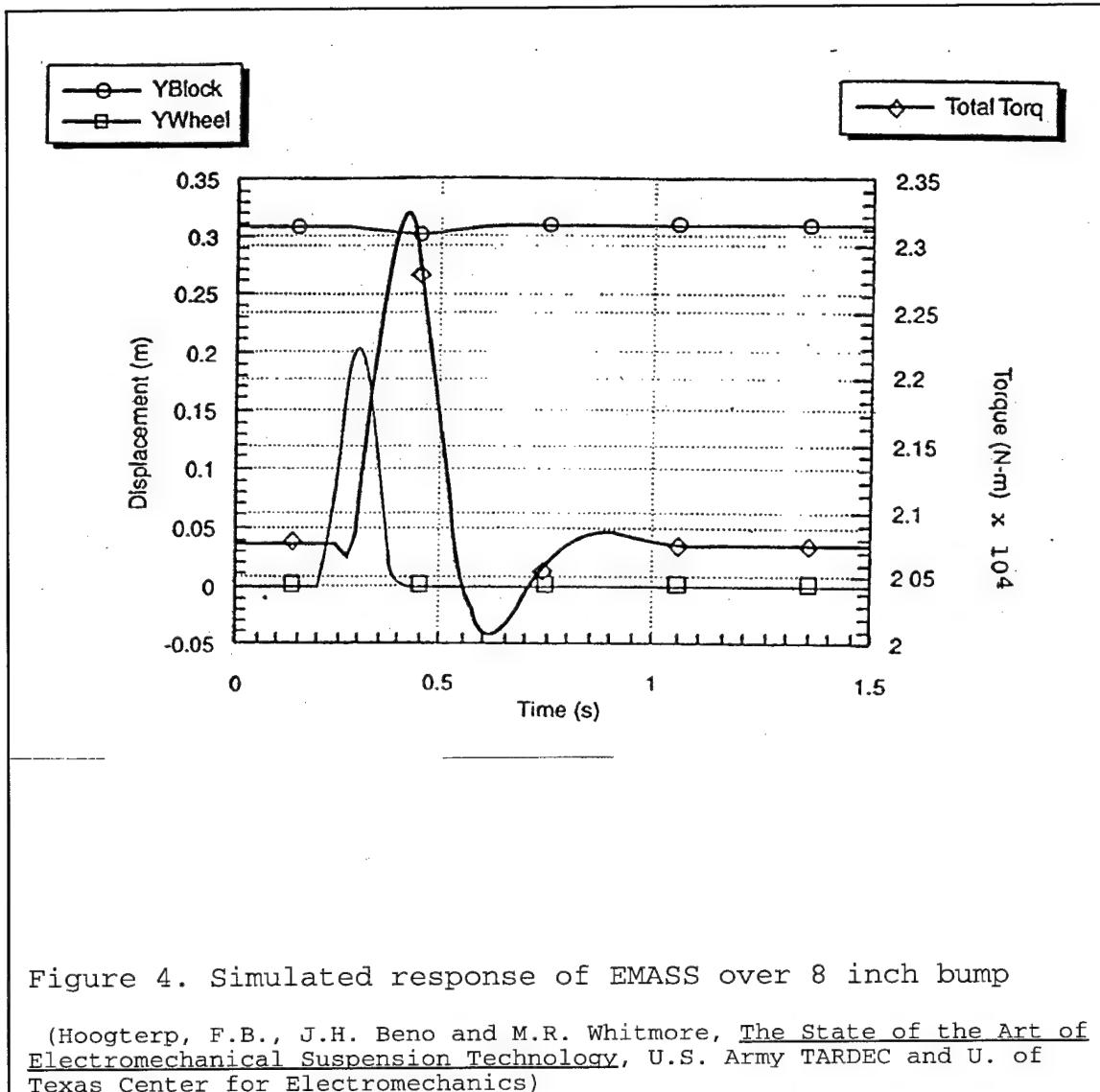
Low equivalent RPM and electronic controls eliminate the need for interpoles or compensating windings to assist commutation. Because the rotor does not rotate in complete circles, but rather oscillates in an arc no more than 60 degrees, brushes and slip-rings were not required.

The control system³ uses open loop control based on road arm position and proportional-derivative closed loop control based on sprung mass vertical displacement. The control system constants were chosen so as to obtain acceptable performance within a defined actuator torque limit of 2250 ft-lb, resulting in a closed-loop damping ratio of 0.5 and a natural frequency of 1.5 hertz. Absolute position encoders are used to provide road arm position feedback to the driver circuits. Position sensors are also mounted on the road wheel and on the sprung mass. The controller system was designed to operate on a 1 millisecond cycle time, as compared to the 6 ms commutation time required for operation at 40 MPH on a 3.486" RMS terrain. Reasons for selecting a short controller cycle time, was to improve commutation and also to compensate for filtering and averaging techniques which require 2 to 5 cycle times.

The controller drives four servo amplifiers, one for each actuator phase winding. The controllers use information from the road arm angle sensor to determine when to commutate (reverse) the current, as well as how much torque (hence current) is needed. In designing control hardware and software for EM actuators, one factor that must be taken into account is torque ripple, as the moving element moves over one or more commutation cycles. In the EMASS system, use of lookup tables reduces torque ripple, thus reducing possible excitation of high frequency vibration modes.

Experimental runs with the one-roadarm EMASS test setup on a simulated 3.486" RMS terrain at 40 MPH, demonstrate ride quality comparable with a passive M1 Abrams suspension at 15 MPH on the same terrain. This was accomplished without the aid of look-ahead technology. Figure 4 illustrates simulated response of the single-wheel test setup to an 8 inch bump. Note that "Y block" (displacement of the 5 ton concrete weight serving as simulated sprung mass) shows very little vertical

motion.



Analysis shows that if an efficient active suspension can be devised and built, the energy needed to activate it can be less than the energy invested in moving the sprung mass up and down as a vehicle operates on undulating terrain.⁴

The EMASS actuator weighs 1000 Lbs (454 Kg). Several opportunities exist to reduce actuator mass.⁵ One could use reduction gearing, which would reduce torque requirements and

hence enable a more compact and lighter unit. Installing the EM actuator on fewer than all 14 roadarms on an M1 would also reduce total weight penalty. Professor Beno also suggests integrating the magnetic circuit's back iron into the vehicle's armor configuration. Finally, use of the more efficient reluctance principle (see below) could bring substantial reduction in weight.

A disadvantage of the rotary electromechanical suspension configuration for the Abrams MBT, is that a dual rate air spring is utilized. This creates potential combat vulnerability. Another disadvantage is need for water cooling, which is necessary to attain high current densities needed to minimize overall size and weight, without excessive temperature buildup.

UT-CEM has worked with the Houston Metro Transit Authority in a joint program to develop EM actuators for transit buses⁶. These vehicles tend to possess low sprung to unsprung mass ratios (especially when carrying few passengers), hence passive suspensions perform poorly. For commercial as well as military vehicles, reducing sprung mass motion would reduce dynamic impact on road surfaces, thus reducing road damage.

In High Performance Linear Actuator for Electromechanical Active Suspension System. Professor Beno considers three types: Voice coil (so named because the basic configuration of a moving coil in a magnetic field is similar to that of a loudspeaker), moving magnet, and induction. Considering none of these types satisfactory for suspension applications, UT-CEM developed their own actuator. They have proposed building prototypes for application to transit buses and the HMMWV, provided they can get the necessary funding.

A conceptual view of the UT-CEM actuator design is shown in Figure 5. Note that there are two stator windings, so as to enable the unit to develop force in either direction. The shuttle surrounds the windings. This design is similar in operating principle to the SatCon linear reluctance actuator designed for the CUCV (see below). The UT-CEM design will be sized for the HMMWV, and hence will have to develop up 1,000 to 1,500 lb. of force.

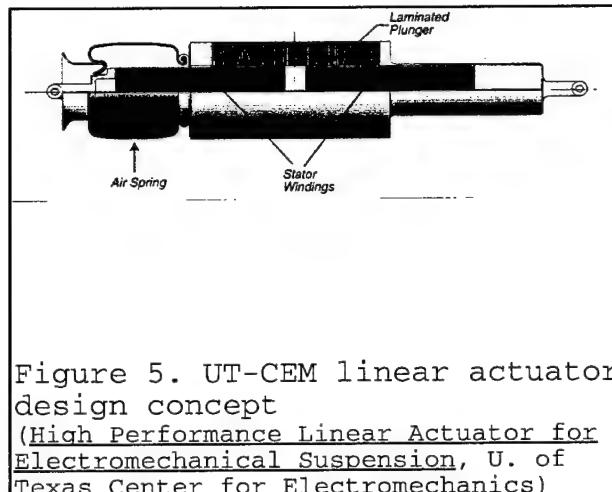


Figure 5. UT-CEM linear actuator design concept
(High Performance Linear Actuator for Electromechanical Suspension, U. of Texas Center for Electromechanics)

On July 11 1996, a kick-off meeting was held at U.S. Army TARDEC in Warren MI, during which Professor Beno presented a briefing on EM suspension programs at UT-CEM. Thus far, an M1 Abrams single wheel proof of concept test bed (described above) has been completed. Multi-wheel control algorithms and test platforms are under development. A 0.3-scale M1 test stand in which four actuators are tested together, has been built for the purpose of developing algorithms for control of roll and pitch, as well as simple bounce motions. The UT-CEM suspension demonstration program includes linear actuator development; performance, thermal, acoustic, and durability testing; design for manufacturing, and technology demonstration.

5.2 Linear Electromechanical Actuator Studies for the CUCV⁷

FMC Corporation⁸ (Now part of United Defense) had performed studies on high torque density electric drive motors for tracked vehicles. On the basis of their studies, they determined that electrical devices could achieve high force densities needed for suspension actuators. Studies using the NATO Reference Mobility Model were carried out on various CUCV suspension configurations. They finally decided to concentrate on two active suspension actuator concepts: The tubular linear induction machine (TLIM) and tubular linear permanent magnet

machine.

FMC concept studies show that for the CUCV, an actuator with +300, -300 lb. force capability is equivalent to a passive system with 265 lb. jounce and 520 lb. rebound capability.

The device topology for a TLIM is as shown in Figure 6. The stator coils are excited with polyphase alternating current, and by controlling the phase sequencing, one can attain motion of the cylindrical conductor in either direction. The CUCV TLIM actuator, shown in Figure 7, operates with 3-phase alternating current. The armature is iron with slots

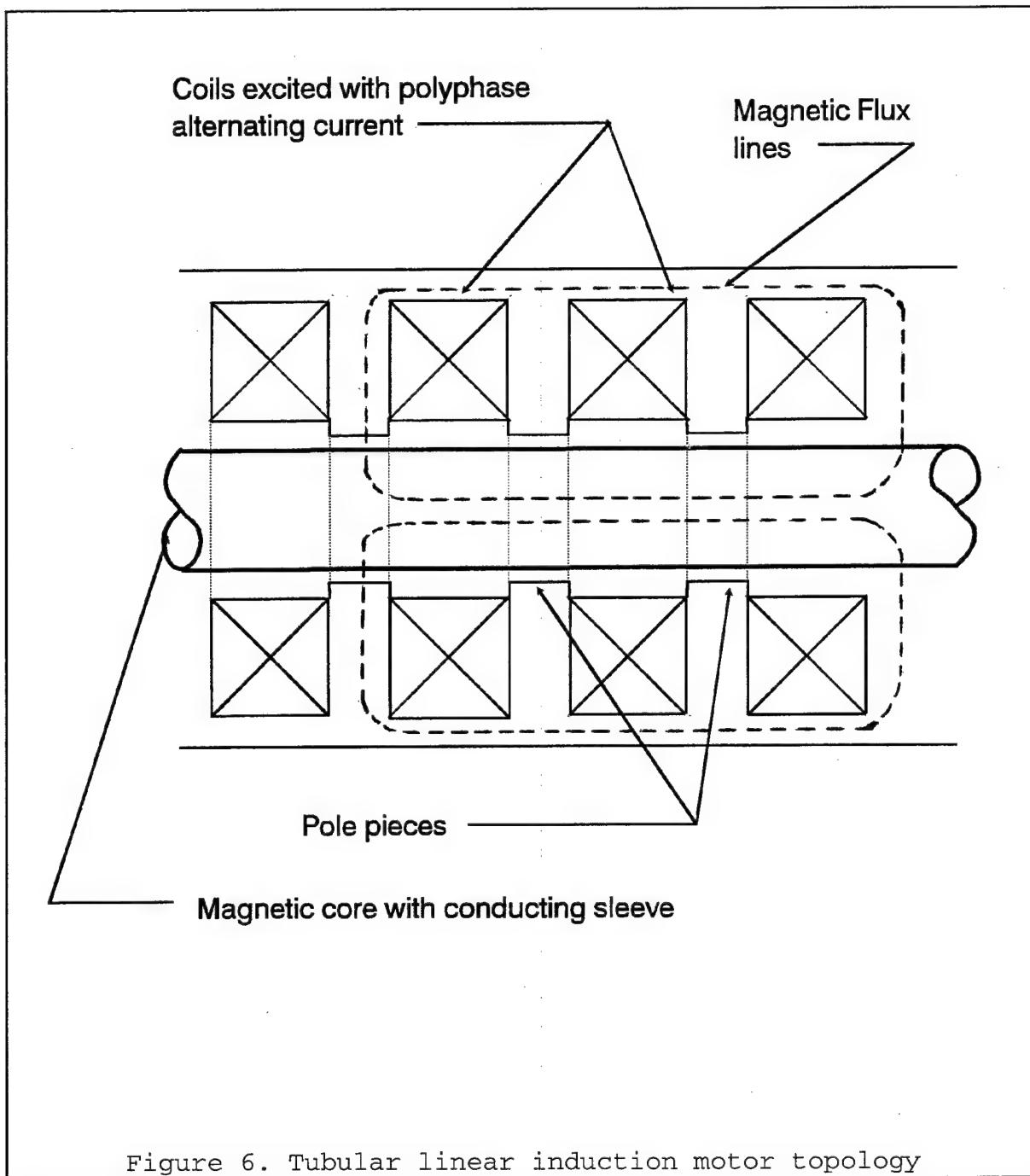


Figure 6. Tubular linear induction motor topology

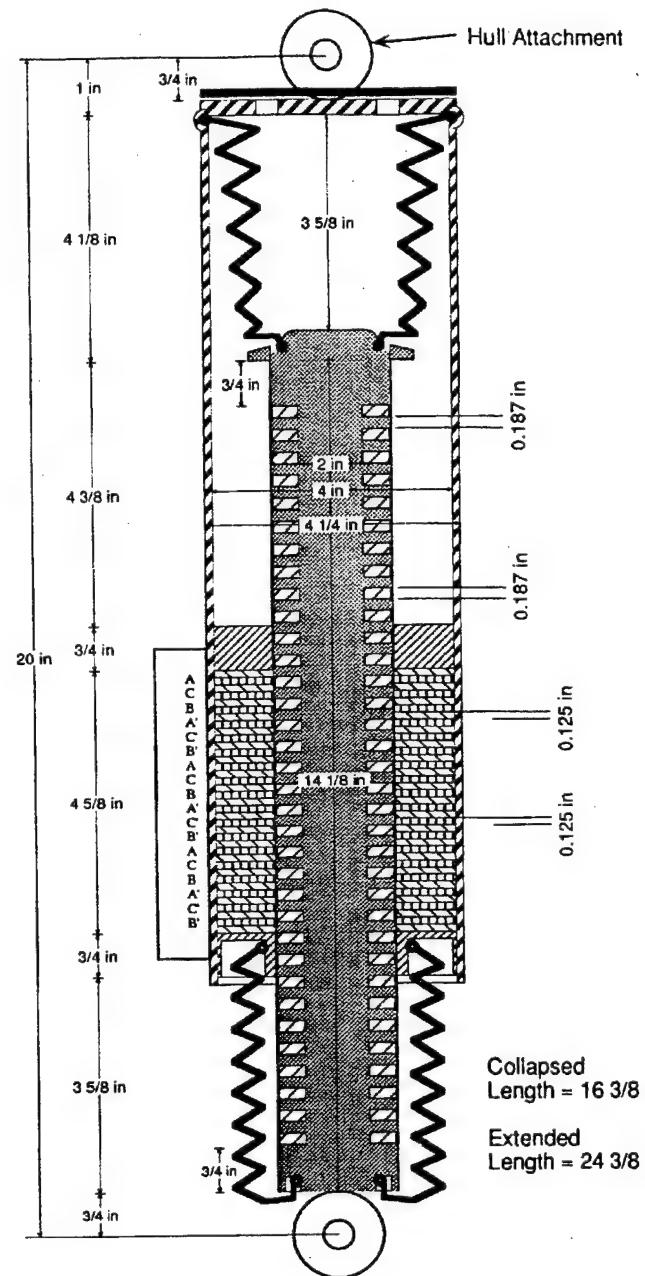


Figure 7. FMC tubular linear induction actuator design
(from FMC draft submittal under Contract DAAE07-91-C-R089)

filled with copper or aluminum. The collapsed length is 16-3/8" while the extended length is 24-3/8", which means 8" stroke length. With 6 poles, the actuator develops up to 855 lb force and is regenerative with the proper electronic controls.

FMC worked with Aura, Incorporated to submit a proposal for a tubular linear permanent magnet actuator. In the FMC report cited above, it was described as a brushless DC design that can be operated at low DC voltage, i.e., 12 or 24 V. It has a stroke length of 8 inches and develops up to 500 lb at stall. Efficiency is quoted at 90% at 12 or more inches per second. Peak current demand was quoted to be 15 amperes.

Under two consecutive contracts, the Army sponsored two electromechanical actuator design studies for the CUCV: a permanent magnet DC type and a linear reluctance machine⁷. The permanent magnet actuator was developed by CMTG Research, Inc⁹. It is a brush commutated coaxial linear DC machine, offering a 10 inch stroke. The design calls for water cooling, to avoid temperatures in excess of what the permanent magnets can tolerate.

The linear reluctance actuator was designed by SatCon Technology Corporation of Cambridge, Massachusetts¹⁰. SatCon had been studying linear actuators for the Naval Undersea Warfare Center (for torpedo control surface actuation) and NASA (for robotics applications). The reason for their choice of the linear reluctance principle is that it offers higher efficiency than induction machines. Furthermore, the allowable temperature limit is higher as there are no permanent magnets, which are susceptible to loss of magnetic performance at elevated temperatures. Air cooling is utilized for thermal management.

Reluctance machines have salient poles on both the rotor (or "shuttle", if the machine is linear) and stator (Figure 8)¹¹. Production of torque or force occurs when the rotor or shuttle moves so as to seek the position of least magnetic circuit reluctance, hence the name. By using polyphase windings for the rotor and choosing stator and rotor/shuttle pole pitch so that pole alignment varies cyclically, and by using polyphase AC or electronically switched DC, one can produce continuous force or

torque in the desired direction. Use of switched DC with a reluctance machine requires knowledge of rotor or shuttle position, so current can be applied to the proper phase such that at a particular moment, torque or force in the desired direction results.

The moving element completes a magnetic circuit, and, unlike the rotor or shuttle in an induction machine, does not carry induced electric currents. Hence I^2R losses occur only in the stator, which simplifies thermal management.

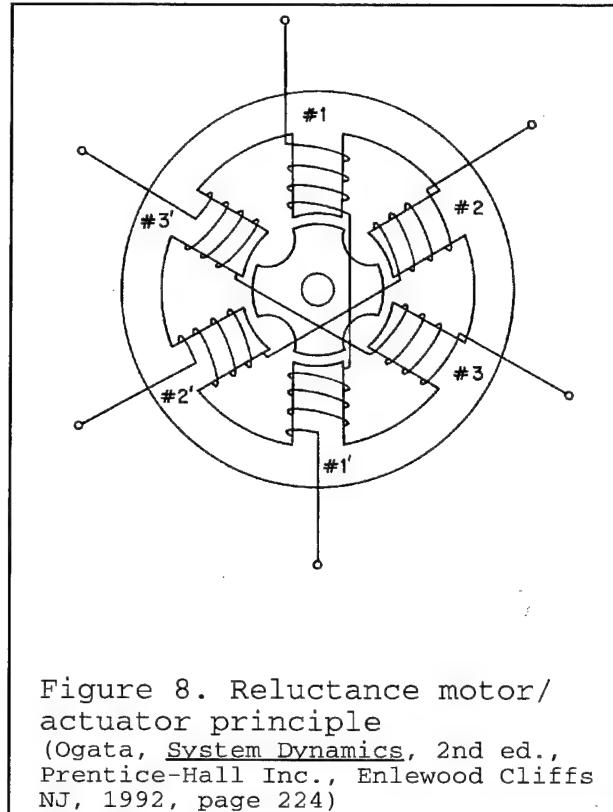


Figure 8. Reluctance motor/actuator principle
 (Ogata, System Dynamics, 2nd ed., Prentice-Hall Inc., Enlewood Cliffs NJ, 1992, page 224)

The SatCon LRM consists of three cylindrical electromagnetic elements arranged concentrically. The outermost and innermost elements are stators. The inner stator is wound, while the outer stator acts as a magnetic return path. The inner stator has a hole in its center for passage of cooling air. The shuttle occupies the annular gap between inner and outer stators. It consists of alternating magnetic and non-magnetic rings, whose pitch is greater than that of the stator pole, so as to bring about the reluctance effect when the inner stator coils are properly energized. While an LRM could be designed with one stator element rather than two, use of inner and outer stator elements in this design increases the force capability of the actuator.

The stroke length is 8.4 inches, which is achieved by making the shuttle that much longer than the stator elements. The former is 24.0", while the latter is 15.6" long. The outer diameter of the actuator is 5.22 inches, so as to fit inside the CUCV coil springs. Maximum peak force is 915 Lbf, and

maximum continuous force when using 20 CFM cooling air, is 423 Lbf. Approximate actuator weight is 100 Lb. The coil windings are three-phase, and are energized by a pulse width modulation inverter. There are four inverters used in the SatCon CUCV electromechanical suspension system, each of which receives its power from a preconverter which converts 28 volts from the vehicle's electrical system to 450 volts DC. The power system is capable of regenerating some power back to the 28 volt bus.

Like the EMASS system, SatCon (and CMTG) active suspension actuators do not bear the static weight of the vehicle. The preferred mode of operation for the SatCon actuator is to provide and absorb force, requiring bi-directional energy flow between the vehicle's 28V electrical bus and the actuator. Adequate air flow must be provided to prevent the windings from becoming too hot. According to SatCon, 200 degrees C (392 degrees F) is the maximum allowable winding temperature. Since a reluctance machine requires no permanent magnets, the limiting factor is temperature tolerance of the stator windings. To promote transfer of heat to a cooling air stream, the central hole (mentioned above) is augmented with longitudinal internal fins which increase the convective heat transfer area.

Another important design consideration is that the unit must be sealed to prevent entry of dust, dirt and other harmful materials; and that bearings be provided to maintain the shuttle in proper alignment with the inner and outer stator elements. The latter is especially important when design is predicated upon maintaining a small air gap.

5.3 Electromechanical Suspension Actuators based on Screw Translation Mechanisms

Ford Motor Company designed and built an electro-mechanical suspension system, and tested it on a Ford Thunderbird. Their design is regenerative, and time-average power consumption is claimed to be 1/3 HP. Weight is claimed to be 200 lb. more than a comparable air suspension. Because of the system's high projected cost (\$5,000 per vehicle), Ford cancelled the development program.^{7,12,13}

Examination of one of Ford Motor Company's patents¹⁴ (Figure 9) reveals an actuator consisting of a rotary electric motor driving a ball-screw mechanism. Note that utilization of a screw-type mechanism to translate rotary to linear force (and

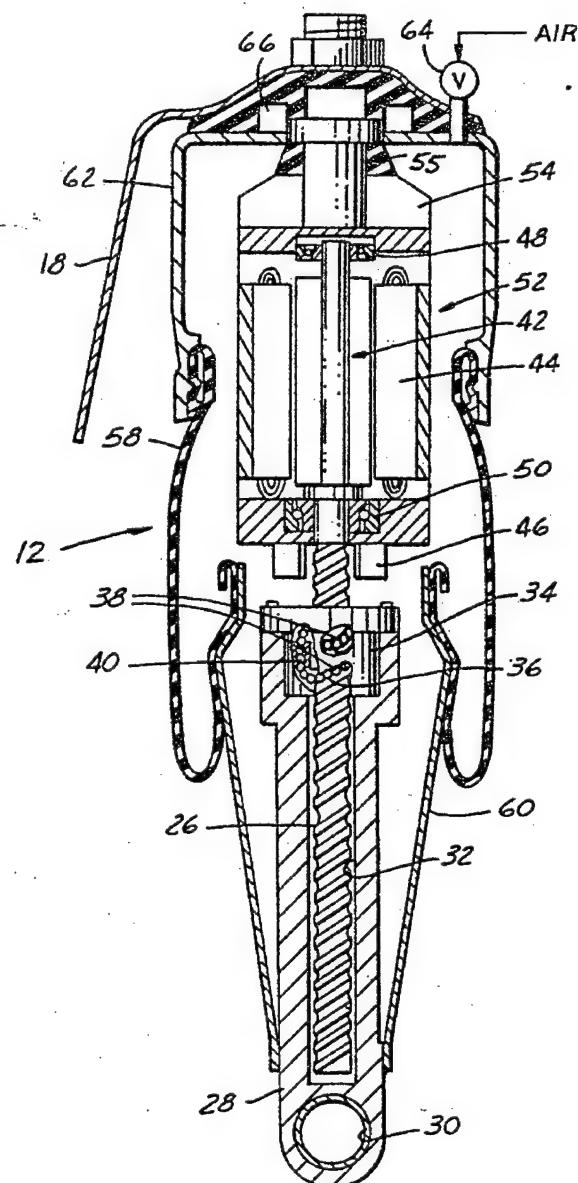


Figure 9. Ford Motor Company ball-screw active suspension actuator patent

vice-versa, during regeneration) is also employed in the electrorheological fluid-based shock absorber designed by UMTRI and tested on a HMMWV quarter-car test stand.

The Ford patent states that the actuator may be used alone or in parallel with a static load carrying device (i.e., suspension spring) and that the motor may be any of a number of types. In practice, one would use this device to add to or subtract from the force of a suspension spring. One possible embodiment of this patent is use of a permanent magnet, electronically commutated direct current motor. Reluctance or induction motors are also a possibility.

T. Hiromatsu of Isuzu Motors Heavy Duty Vehicle Research & Experiment Department¹⁵ describes another suspension actuator in which a rotary motor drives a screw mechanism to obtain linear motion. Here, the purpose is to isolate a truck cab from the frame so as to reduce driver fatigue. The system was built and tested, demonstrating substantial reduction in cab motion with a servo motor described by the authors as rated at 100 watts. H-infinity control theory was utilized to weight the control system frequency response for optimum results.

A disadvantage of any lead-screw suspension device, whether an electrorheological fluid based damper for use with semiactive suspensions or a motor-driven ball screw actuator for active suspensions, is the friction associated with the screw. With active suspension actuators, the question of response speed (bandwidth) also arises.

6. Developments in Motor and Actuator Concepts Applicable to Electromechanical Active Suspensions

Journals such as IEEE Transactions on Industry Applications and IEEE Transactions on Magnetics, have had technical papers describing developments and improvements of motor/actuator concepts potentially applicable to active suspensions. These concepts include tubular linear induction machines, reluctance machines, and permanent magnet-type motors and actuators using Nd-Fe-B type magnets. Examples of such articles are given below.

Hamid A. Toliyat et al of the University of Wisconsin Department of Electrical and Computer Engineering, devised a synchronous reluctance motor whose windings are excited by a five-phase, pulse width modulated inverter.¹⁶ The current to each phase consists of a fundamental and third harmonic components. Addition of 33% third harmonic to the fundamental frequency, results in 10% higher torque and low torque ripple.

Chris C. Jensen and two co-authors describe an axial-field permanent magnet brushless DC motor using a tape-wound amorphous iron, toroidally wound stator.¹⁷ Use of amorphous iron results in lower magnetic losses than silicon steel. The design developed by Jensen, et al consists of a single amorphous iron-based stator with a rotor on each side, with the magnetic flux aligned in the axial (as opposed to radial) direction. Use of two rotors with a single stator sandwiched between them was dictated by the cost of amorphous iron; having two working surfaces maximizes the utilization of stator material.

The amorphous iron used in the above project is marketed under the trade name METGLAS. Testing of an experimental motor based on the above design concept revealed that eddy current losses in the aluminum frame accounted for a large percentage of measured losses. Eddy current losses are aggravated by current ripple. With careful controller design, one can reduce losses and hence heat buildup problems, in addition to reducing power consumption.

An example of an axial flux, reluctance actuator design is illustrated in Figure 10.⁸

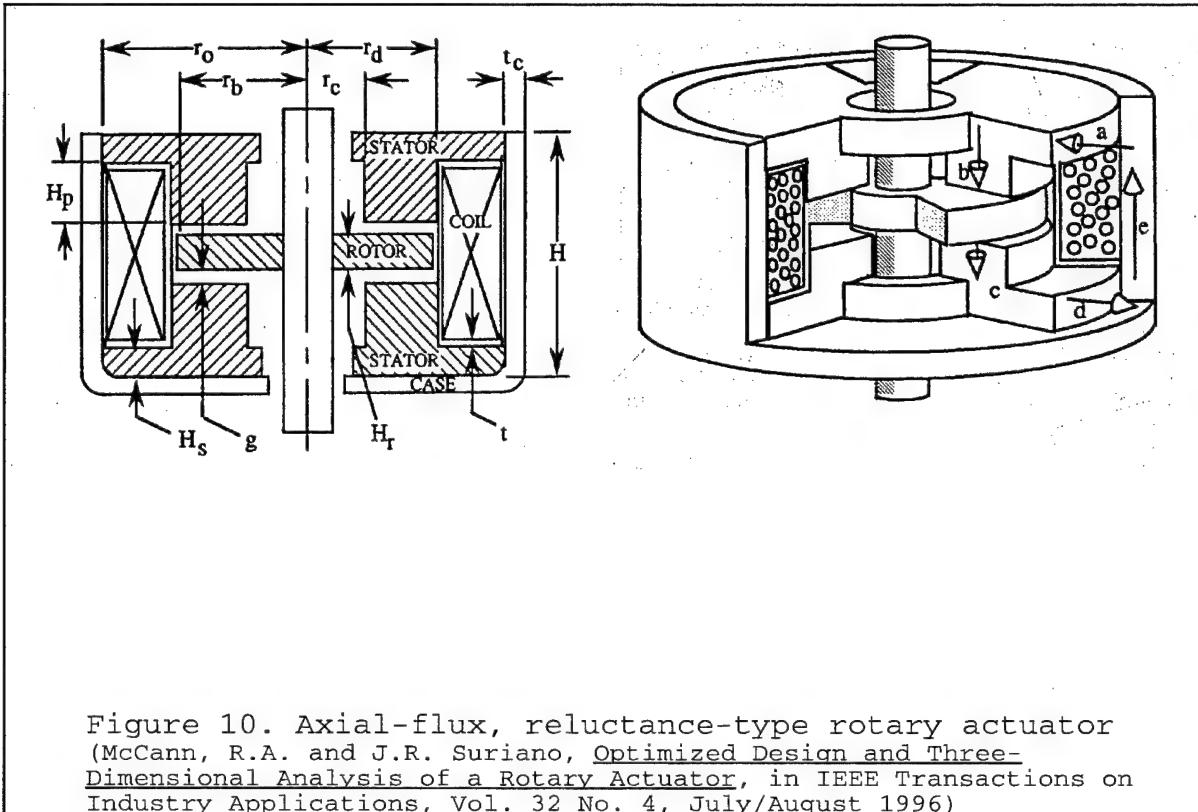
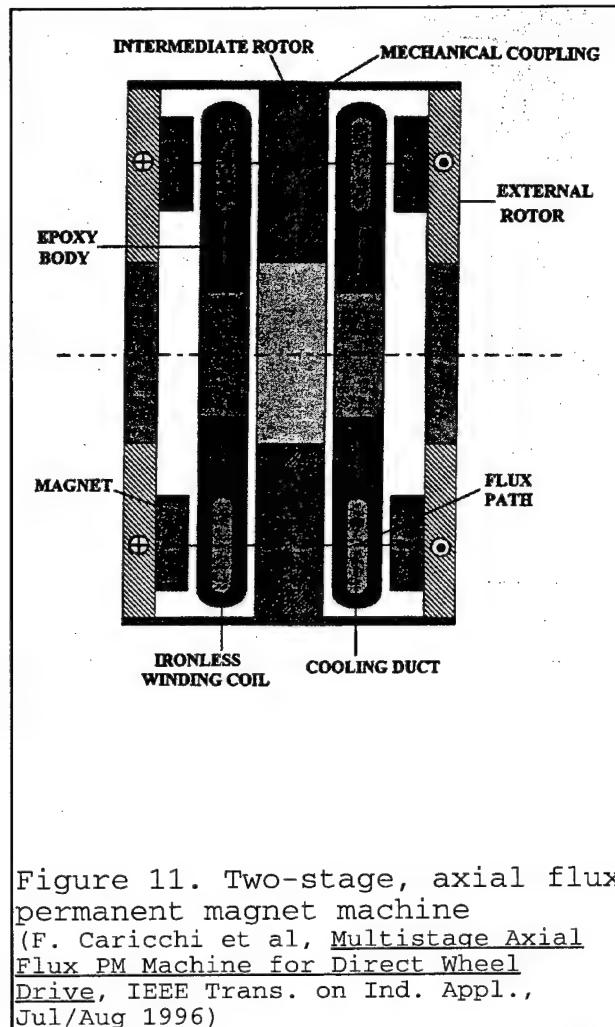


Figure 10. Axial-flux, reluctance-type rotary actuator (McCann, R.A. and J.R. Suriano, Optimized Design and Three-Dimensional Analysis of a Rotary Actuator, in IEEE Transactions on Industry Applications, Vol. 32 No. 4, July/August 1996)

Compact high-torque motors are being developed for direct wheel drive in electric vehicles. One example is a multistage, axial flux, permanent magnet machine designed by researchers at the Department of Electrical Engineering at University of Rome (Figure 11).¹⁹ Their particular design is 320 mm (12.6 inches) in diameter, weighs 26.8 kg (59 lb), and develops 215 Newton-meters torque continuously at 1100 RPM, or 430 Nt-m peak. Because of the utilization of high strength permanent magnet materials in a compact structure, liquid cooling is necessary.



7. Problems, Prospects and Issues with Electromechanical Suspensions

Of the types of actuators studied for vehicle suspensions, all have problems that will have to be considered and resolved. Reluctance actuators offer high efficiency, but suffer the disadvantage of torque ripple, because of the cyclical pole misalignment that is the essence of their principle of operation. Tubular linear induction machines offer high force in proportion to size and mass, but suffer low efficiency.

A good review of tubular linear induction motor theory was written by D.J. De Groot and C.J. Heuvelman in Tubular Linear Induction Motor for use as a Servo Actuator²⁰. The authors built and tested a TLIM, and developed a control strategy for use of this concept as a servo actuator.

S.A. Nasar, G.Y. Xiong, and Z.X. Fu²¹ consider nonlinear B-H characteristics, hysteresis, and skin effect in deriving methods of calculating eddy current losses in TLIM machines, with the aim of reducing such losses while retaining the advantages of simple construction.

Permanent magnet machines utilizing high performance magnet materials offer compact size and high efficiency. An important advantage of permanent magnets as applied to motors and actuators, is that there is no consumption of energy in field windings. Axial permanent magnet machines offer advantage of flat shape. However, it will be necessary to limit operating temperature to avoid demagnetizing such materials. A number of proposed permanent magnet actuator and motor designs utilize liquid cooling to limit operating temperatures, which introduces some of the disadvantages of hydraulic systems. Nd-Fe-B magnets are also vulnerable to corrosion.

T. Sebastian²² claims that Nd-Fe-B magnets can operate at up to 150 degrees C, or 302 degrees F. Motor efficiency tends to decrease with temperature, as does torque when a current limit is set. Temperature compensation may be required. Another technical paper²³ gives 140 degrees C. (284 degrees F) as the maximum operating temperature for Nd-Fe-B permanent magnets.

All EM actuators will have to be designed to operate in a rugged environment. Because of the problems of contamination by undesirable substances present in real-world operating environments, mechanical commutation is not suitable. Also, the commutator and brushes configuration has the disadvantage of wear and tear. Hence AC or electronically switched DC systems are better suited for suspension actuators.

The problem with AC/switched DC motors and actuators has been the need for suitable inverters. The cost of power transistors is a major factor. Fortunately great strides have been made in industrial variable speed drives, thus costs of associated control circuitry are not as much of a problem as they used to be. In addition, the weight of such systems has also come down.

8. Military, Commercial and National Importance of Electromechanical Actuators

The automotive industry will in the future become increasingly internationalized and competitive. Accordingly, the technology of active suspensions is important as far as our nation's industrial posture is concerned. Military vehicles, tracklaying and wheeled, are under demands to be more capable while also meeting requirements such as transportability. There are also efforts to develop all-electric combat vehicles so as to eliminate problems with hydraulics and conventional transmissions. Electromechanical suspension actuators would fit in nicely with the overall design theme of such vehicles.

9. References

1. Ingram, S.K. and Joseph H. Beno, Design, Fabrication, and Test of a High-Torque Rotary Electromechanical Actuator for a Main Battle Tank Active Suspension, Proof-of-Principle Demonstration, University of Texas at Austin Center for Electromechanics
2. Beno, J.H., Hoogterp; Francis B. (U.S. Army TARDEC) et al, Electromechanical Suspension for Combat Vehicles. (SAE Technical Paper 950775)
3. Weeks, D.A., Control System for Single Wheel Station Heavy Tracked Vehicle Electromagnetic Suspension, University of Texas at Austin Center for Electromechanics
4. Beno, J.H.; Hoogterp, Francis B; and Damon W. Weeks; Active Suspension System Energy and Power Requirements for Rough Terrain (Military) Applications, University of Texas at Austin Center for Electromechanics
5. Beno, J.H., Electromechanical Suspension, University of Texas at Austin Center for Electromechanics
6. U. of Texas at Austin Center for Electromechanics, High Performance Linear Actuator (Proposal submitted to Commander, U.S. Army Tank-Automotive Command in 1995)
7. Hoogterp, Beno, Michael R. Whitmore, The State of Electromechanical Active Suspension Technology
8. Concept Design of an Electrical Actuator for the Suspension System of a Commercial Utility Cargo Vehicle (CUCV), submitted by FMC Corporation under Contract DAAE07-91-C-R089, Work Directive No. RY0004, July 1993
9. Non-Hydraulic Suspension Actuators Phase I SBIR Review 4 October 1993, CMTG Research, Inc., North Canton CT. Submitted under Contract DAAE07-93-C-R019

10. Development Study of Non-Hydraulic Suspension Actuators:
Final Report, SatCon Technology Corporation, Cambridge MA, September 1993 Submitted under Contract DAAE07-93-C-R018
11. Ogata, Katsuhiko; System Dynamics (Second Edition), Prentice-Hall Inc., Englewood Cliffs, New Jersey 1992
12. Sawyer, C.A., Active or Adaptive Suspension?, in Automotive Industries, June 1994
13. Keebler, J., Ford Kills Active Suspension Program, in Automotive News, Jan 23 1995
14. U.S. Patent No. 5,060,959, granted to R.I. Davis et al., of Ford Motor Company October 29, 1991.
15. Hiromatsu, Takashi, T. Inaba, and Y. Matsuo (Tokyo Institute of Technology), Development of an Electromechanical Active-Cab Suspension
16. Toliyat, Hamid A., L. Xu and Thomas A. Lipo (University of Wisconsin Department of Electrical and Computer Engineering), A Five-Phase Reluctance Motor with High Specific Torque, in IEEE Transactions on Industry Applications, Volume 28, No. 3, May/June 1992, pages 659-667
17. Jensen, Chris C., Francesco Profumo, and Thomas A. Lipo, A Low-Loss Permanent Magnet Brushless DC Motor Utilizing Tape Wound Amorphous Iron, in IEEE Transactions on Industry Applications, Vol 28 No. 3, May/June 1992, pages 646-651
18. McCann R.A. and J.R. Suriano, Optimized Design and Three-Dimensional Finite Element Analysis fo a Rotary Actuator, published in IEEE Transactions on Industry Applications, Volume 32 No. 4, July/August 1996, pages 867-872
19. Caricchi, Federico et al, Multistage Axial-Flux PM Machine for Wheel Direct Drive, in IEEE Transactions on Industry Applications, Volume 32 No. 4, July/August 1996, pages

20. De Groot, D.J. and C.J. Heuvelman, Tubular Linear Induction Motor for use as a Servo Actuator, published in IEE Proceedings, Volume 137, Part B, No 4 (July 1990), pages 273-280
21. Nasar, S.A., G.Y. Xiong and Z.X. Fu, Eddy Current Losses in a Tubular Linear Induction Motor (IEEE Transactions on Magnetics, Volume 30, No. 4, July 1994), pages 1437-1444
22. Sebastian, T., Temperature Effects on Torque Production and Efficiency of PM Motors Using NdFeB Magnets (IEEE Transactions on Magnetics, Vol. 31, No. 2, March/April 1995, pages 353-357)
23. Shenton, A.T. and P.H. Mellor, Fundamental Requirements for High-Performance Electro-Mechanical Actuators for Aerospace and Active Suspension Applications (Proceedings of the 2nd International Technology Transfer Congress; Bremen, Germany, June 1990, pages 206-210)

Distribution List

COPIES**ADDRESS**

2

Defense Technical Information Center
Cameron Station
Alexandria, VA 22314

10

Commander
U.S. Army Tank-Automotive Research, Development
and Engineering Center
ATTN: AMSTA-TR-R, Bldg. 215, MS 159
Warren, MI 48397-5000